ECMWF and SSMI Global Surface Wind Speeds

David Halpern[1], Anthony Hollingsworth[2] and Frank Wentz[3]

[1] Earth and Space Sciences Division
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
U.S.A.

[2] European Center for Medium-Range Weather Forecasts
Shinfield Park
Reading, Berkshire RG2 9AX
UNITED KINGDOM

[3] Remote Sensing Systems, Suite 220
1101 College Avenue
Santa Rosa, CA 95404
U.S.A.

ABSTRACT

Monthly mean, 2.5°- x 2.5°-resolution, 10-m height wind speeds from the Special Sensor Microwave Imager (SSMI) instrument and the European Center for Medium-Range Weather Forecasts (ECMWF) forecast-analysis system are compared between 60°S and 60°N during 1988 - 1991. The SSMI data were uniformly processed while numerous changes were made to the ECMWF forecast-analysis system. The SSMI measurements, which were compared with moored-buoy wind observations, were considered to be a reference data set to evaluate the influence of the changes made to the ECMWF system upon the ECMWF surface wind speed over the ocean. A demonstrable yearly decrease of the difference between SSMI and ECMWF wind speeds occurred in the 10°S - 10°N region, including the 5°S - 5°N zone of the Pacific Ocean, where nearly all of the variations occurred in the 160°E - 160°W region. The apparent improvement of the ECMWF wind speed occurred at the same time as the yearly decrease of the equatorial Pacific SSMI wind speed, which was associated with the natural transition from La Niña to El Niño conditions. In the 10°S - 10°N tropical Atlantic, the ECMWF wind speed had a 4-year trend, which was not expected nor was it duplicated with the SSMI data. No yearly trend was found in the difference between SSMI and ECMWF surface wind speeds in middle latitudes of the northern and southern hemispheres. The magnitude of the differences between SSMI and ECMWF was 0.4 m s^{-1} or 100% larger in the northern than in the southern hemisphere extratropics. In two areas (Arabian Sea and North Atlantic Ocean) where ECMWF and SSMI wind speeds were compared to ship measurements, the ship data had much better agreement with the ECMWF analyses compared to SSMI data. In the 10°S - 10°N area the difference between monthly standard deviations of the daily wind speeds dropped significantly from 1988 to 1989, but remained constant at about 30% for the remaining years.

1. Introduction

Studies of seasonal-to-interannual global air-sea fluxes of heat and gases, including carbon dioxide and water, require surface wind speed data at time and space resolutions of about one month and one- to two-hundred kilometers. To compute a monthly mean surface wind speed, frequent measurements are needed to describe diurnal-period and other submonthly variations (Halpern 1988a; Legler 1991). Wind speeds need to be measured at relatively close spacing to resolve the natural spatial variability produced by ocean-atmosphere phenomena such as the western boundary current, equatorial upwelling, and the Intertropical Convergence Zone (ITCZ). For more than a century the large-scale distribution of wind speed has been measured from ships. As well as uncertainties created by the varying heights of anemometers within the constant stress layer and the variety of wind-measuring techniques on ships, the worldwide sampling distribution of ship observations was, and continues to be, very uneven. Frequent wind measurements at fixed sites are extremely rare, although the situation has marginally improved recently because of international programs like the Tropical Ocean Global Atmosphere (TOGA) Program. Ships seldom visit regions south of about 20°N except along a few narrow lanes. The surface wind field over immense regions of the southern hemisphere ocean is not measured for many successive months.

For many years, estimates of the surface wind field over the global ocean have been data products routinely generated in operational numerical weather prediction (NWP) centers (Halpern et al. 1982). One such data product is produced at the European Center for Medium-Range Weather Forecasts (ECMWF), where, typical of all operational NWP centers, the forecast-analysis system is continually undergoing change. The current widespread usage of ECMWF surface winds warrants the examination of the effects of the many changes upon the ECMWF surface wind data product.

A technological achievement occurred in 1978 to reduce our dependence on the highly aliased wind observations from ships, when, for three months, global surface wind speed and wind vector measurements were determined from microwave electromagnetic radiation measurements recorded by the SEASAT spacecraft. Other spacecraft with surface wind speed measurement capabilities followed SEASAT. With the launch of the United States (U.S.) Air Force Defence Meteorological

Satellite Program (DMSP) Special Sensor Microwave Imager (SSMI) in July 1987, surface wind speeds were continuously measured over the global ocean approximately every 3 days. A uniform data processing procedure of the SSMI measurements enabled the SSMI wind speed time series to represent a reference data set for evaluation of the impact of the changes made to the ECMWF forecast-analysis system upon the ECMWF surface wind speeds. This paper describes the time-varying relationship between ECMWF and SSMI surface wind speeds from January 1988 to December 1991. Because the SSMI does not estimate wind direction, there is no evaluation of the ECMWF surface wind velocity components, which are very important for studies of ocean circulation dynamics.

2. Data Sets

a. SSMI wind speed

The SSMI is a 7-channel, 4-frequency, linearly polarized, passive microwave radiometer flown on the DMSP spacecraft F8. The second and third SSMI instruments were launched on DMSP spacecraft F10 and F11 in December 1990 and November 1991, respectively. Only F8 measurements are used in this paper.

The intensity of microwave radiation emitted at the ocean surface is affected by sea surface roughness, which is correlated with surface wind speed. Remote Sensing Systems (RSS) of Santa Rosa, California, used the Wentz (1989, 1992) procedure to process the SSMI 37-GHz vertically and horizontally polarized brightness temperature observations into 10-m height wind speeds. The RSS data processing procedure, which did not utilize in-situ wind measurements, remained unchanged between January 1988 and December 1991. The RSS-derived wind speeds were obtained from the National Aeronautics and Space Administration (NASA) Ocean Data System (Halpern 1991).

The SSMI wind speeds occurred in nonoverlapping areas of 25 km x 25 km, which were arrayed across the 1394-km swath width. All speeds located within nonoverlapping 1/3° x 1/3° squares were arithmetically averaged each day. The 1/3° x 1/3° area was chosen to correspond to the horizontal grid of an ocean general circulation model used to simulate wind-driven upper-ocean currents in the tropical Pacific, and because it is the pixel size of a number of satellite-derived data products published in a series of atlases (e. g., Halpern et al. 1993). Most 1/3° x 1/3° areas contained about two wind measurements per day. Areas with large amounts of atmospheric moisture, such as the ITCZ and the South Pacific Convergence Zone, contained about one wind speed measurement per day. If the total liquid water content throughout the atmosphere was greater than 0.25 kg m^{-2}, then the wind speed algorithm was considered invalid because there would be too much radiative scattering from water droplets.

For each month, a mean value and a standard deviation of the daily values were computed from the daily averaged 1/3° x 1/3° wind speeds. Global distributions of monthly mean wind speed and monthly standard deviation of daily wind speeds were presented in a series of atlases (e. g., Halpern et al. 1993). In order that the SSMI data have the same grid dimensions as the ECMWF data product, the 1/3° x 1/3° monthly mean and variance values were each arithmetically averaged within nonoverlapping 2.5° x 2.5° regions. Throughout 1988 - 1991 there were nearly 1200 1/3° x 1/3° SSMI values per month within each 2.5° x 2.5° area between 60°S and 60°N.

The accuracy of monthly mean 2/3° x 2/3° SSMI wind speeds was determined by comparison with moored-buoy wind measurements (Figure 1A) at about 60 sites in the Atlantic and Pacific Oceans during January 1988 - December 1991 (Halpern 1993). All moored-buoy wind observations, which were recorded at 3.5- to 11.0-m heights, were referenced to 10 m. Buoys were approximately evenly distributed between low and middle latitudes. In middle latitudes where wind speeds greater than 10 m s^{-1} occur for many months (Esbensen and Kushnir 1981; Halpern et al. 1993), a moored-buoy anemometer would conceivably underestimate the actual wind speed because the anemometer would be shielded from the full wind speed when the surface-following buoy was in a surface wave trough deeper than the height of the anemometer. This condition rarely occurred in low latitudes where the wave trough was almost always less than the anemometer height and where the 40-day mean moored-buoy wind speed error caused by motion of a surface-following buoy was 0.2 m s^{-1} or 3.5% of the mean wind speed computed from 15-

min measurements (Halpern, 1987).

The root-mean-square (rms) difference of 1211 monthly mean SSMI and moored-buoy wind speed matchups during January 1988 - December 1991 was 1.1 m s^{-1}, which was considerably less than the 3 - 4 m s^{-1} rms accuracy of transient wind measurements recorded by ships (Esbensen et al. 1993). The 4-year mean SSMI wind speed was 0.1 m s^{-1} greater than that computed from the moored-buoy measurements, in marked contrast to the 1 - 2 m s^{-1} bias between ship and buoy data (Esbensen et al. 1993). The range of the moored-buoy monthly mean wind speeds was 2 to 11 m s^{-1}. The correlation coefficient between SSMI and buoy matchups was 0.8, which was significant at the 95% confidence level. Statistical results of the annual matchups were nearly the same for each of the four years. Also, the SSMI and moored-buoy monthly standard deviations of daily wind speeds (Figure 1B) were compared. Over the 0.5 - 4.6 m s^{-1} range of the monthly buoy standard deviations, the correlation coefficient was 0.9. The rms difference and bias were 0.4 and 0.2 m s^{-1}, respectively. Statistical results of the annual matchups of monthly standard deviation of daily wind speeds were the same for each of the four years.

b. ECMWF wind speed

The ECMWF forecast-analysis system, like all operational atmospheric forecast-analysis systems, is very complex and forecasts are continually being improved. The ECMWF forecast-analysis system assimilates measurements from a variety of sources, such as radiosondes, buoys, ships, aircraft, cloud-tracked drift, and satellite soundings. In the near-surface constant-stress layer, wind observations are recorded from buoys and ships; however, wind measurements at different wind-sensor heights at buoys and ships are not referenced to a uniform height. The 10-m height winds were derived from the lowest model-level winds at 30 m and a stability dependent boundary layer model from the multivariate mass and wind analysis. The ECMWF analysis is performed four times daily and SSMI wind speeds were not used. Portions of the 1988 - 1991 ECMWF World Climate Research Program Tropical Oceans Global Atmosphere (WCRP/TOGA) Basic Level III Global Surface Grid Point Data Set, which is published twice daily at 0000 and

1200 Greenwich Mean Time (GMT), were obtained from ECMWF on three occasions: 1 January 1988 - 31 March 1989 in July 1989; 1 January 1990 - 30 June 1991 in September 1991; 1 July - 31 December 1991 in July 1992. The 1 April - 31 December 1989 wind analyses were received from the National Center for Atmospheric Research (NCAR).

A thorough description of the development of the ECMWF forecast-analysis system since its initiation in 1979 was given by Hoskins et al. (1989), who listed 27 important changes in the forecast model and analysis procedure from 1979 to the end of 1987. For instance, in 1985 there were major changes in the parameterizations of clouds, convection and condensation. Further description of the ECMWF global fields was given by Trenberth (1992), who cited 14 changes from January 1988 to September 1991. The *ECMWF Newsletter* (available from ECMWF, Reading, United Kingdom) describes changes as they occur.

The ECMWF 10-m height wind speed, S_{ECMWF}, was computed at 12-h intervals: $S_{ECMWF} = (u^2 + v^2)^{1/2}$, where u and v are the ECMWF east-west and north-south wind components, respectively. The areal size of each element was 2.5° x 2.5°. For each month, a mean value and a standard deviation of the daily mean values were computed from the daily averaged 2.5° x 2.5° wind speeds, and displayed in a series of atlases (e. g., Halpern et al. 1993).

3. Results

a. Global Aspects

All comparisons are confined to the global ocean from 60°S to 60°N to avoid incorrect interpretations caused by uneven temporal sampling of SSMI winds associated with the seasonal migration of sea ice near Antarctica. The geographical outline of the global ocean is shown in Figure 2. The equator separates the northern and southern hemisphere oceans while the 20°E, 145°E, and 70°W longitudes separate the South Atlantic and South Indian, South Indian and South Pacific, and South Pacific and South Atlantic Oceans, respectively.

The 4-year 2.5° x 2.5° average global distributions of SSMI and ECMWF wind speeds and of their respective monthly standard deviations of daily values have many common features (Figure

2). The 4-year mean SSMI and ECMWF wind speed distributions (Figures 2A and 2B) are both similar to climatology (Esbensen and Kushnir 1981; Hsiung 1986). Lowest wind speeds occur in the equatorial zone. Wind speeds increase poleward from the equator, with the largest wind speeds in the 60 - 50°S band. The ratio of the 55°S wind speed to the wind speed at 0° was approximately 2. The smallest submonthly standard deviations occur in the equatorial zone. Along the Pacific equator at 140, 125, 110 and 95°W, the 4-year average monthly standard deviations of SSMI daily wind speeds (Figure 2C) were less than 10% smaller than that recorded from moored buoys for a year (Halpern, 1988b). Submonthly standard deviations increase poleward from the equator, with the largest standard deviations in the 50 - 60°N band. The ratio of the submonthly standard deviations at 55°N to that at 0° was about 3. In the equatorial Pacific, the intensity of the day-to-day variability of wind speed, which is represented by the submonthly standard deviation (Figures 2C and 2D), increased from east to west, which was initially noted by Halpern (1989). The possible suppression of surface wind fluctuations by the cold water in the eastern region compared to the increased wind variability over the warm water in the western Pacific is being investigated (Halpern in preparation).

Area-weighted monthly mean SSMI and ECMWF wind speeds were computed for each ocean basin between 60°S and 60°N and for the northern and southern hemisphere portions of each ocean basin within 60° latitude. Of the nine 48-month time series, the only regions where the 4-year mean SSMI and ECMWF differences were significant were the Pacific Ocean and the South Pacific Ocean. In these regions the monthly mean SSMI wind speeds were approximately 0.5 and 0.7 m s^{-1}, respectively, greater than the corresponding ECMWF speeds. Also, for each of the two aforementioned regions, the annual mean difference between SSMI and ECMWF wind speeds was significant for each of the four years. The Student's *t*-test is used to establish the significance of a difference of mean values (Press et al. 1986). The level of statistical significance used throughout the paper is 95%.

Longitudinal averages of the SSMI and ECMWF wind speeds were computed in 2.5°-latitude intervals. In the 4-year averaged north-south profiles (Figure 3A), which were representative of the annual mean profiles, SSMI speeds were greater than ECMWF values everywhere except between approximately 30 - 50°N. The SSMI-ECMWF wind speed difference (about 0.4 m s^{-1}) in the 50 - 30°S zone was approximately one-half the magnitude of the difference (-0.8 m s^{-1}) in the corresponding zone of the northern hemisphere. Guillaume and Hansen (personal communication 1993) found a similar result between monthly mean ECMWF wind speeds and those computed from the European Space Agency European Remote Sensing (named ERS-1) satellite altimeter measurements recorded during 1992. We did not *a priori* expect the SSMI and ECMWF correspondence to be better in the southern hemisphere, where fewer surface meteorological observations were assimilated into the ECMWF forecast-analysis system.

The marked differences between SSMI and ECMWF winds in the 30 - 50°N band could be due to the use of ship wind measurements. To test this suggestion, we looked at the wind speeds in the 30 - 50°N, 40 - 20°W area of the North Atlantic Ocean, where the 4-year mean difference between ECMWF and SSMI was significant and where the quantity of surface meteorological observations from ships was among the most plentiful over the global ocean. We obtained the 1988 - 1991 ship measurements of wind speed for the 30 - 50°N, 40 - 20°W region of the North Atlantic Ocean from the NCAR Comprehensive Ocean-Atmosphere Data Set (COADS) Compressed Marine Reports. Ship wind speeds were referenced to 10-m height by a constant 6% reduction corresponding to an anemometer height of 19.5 m. The approximate 4000 ship observations recorded each month, which were nearly evenly divided between anemometer measurements and Beaufort estimates of wind speed, were uniformly distributed throughout the area. During each of the three winter (December - February) seasons the Beaufort estimated wind speed was 0.5 - 1.0 m s^{-1} greater than the anemometer wind speed; the opposite situation occurred during each summer (June - August) interval. The COADS included both delayed-mode measurements and real-time wind data transmitted on the Global Telecommunications System (GTS), which was used by ECMWF (and other NWP centers) to retrieve ship observations for the forecast-analysis system. During 1988 - 1991 approximately two-thirds of the total number of COADS data were transmitted on the GTS. The monthly mean ECMWF analyzed wind speeds in the Atlantic virtually reproduced the time evolution of the COADS data (Figure 4). Monthly mean COADS data were usually an insignificant 0.1 m s^{-1} greater than the ECMWF wind speeds. The 4-year average difference between COADS and ECMWF was not significant, nor were the annual mean differences. However, the 4-year average difference of 0.9 m s^{-1} between COADS and SSMI data was significant.

We attribute the nearly equal zonally averaged SSMI and ECMWF wind speeds within 30 - 50° latitude in the southern hemisphere (Figure 3A) to the near absence of ship observations in this latitudinal zone. This was in marked contrast to the situation in the same extratropical latitudes in the northern hemisphere where ship measurements were very plentiful and where ECMWF wind speeds were greater than SSMI measurements (Figures 3A and 4). Ship measurements of wind speed are probably biased high relative to 10 m because anemometer heights on modern container vessels are 25 - 30 m (Cardone et al. 1990). Another possible bias in COADS winds in the North Atlantic Ocean is that nearly 50% of COADS wind speeds were determined from Beaufort estimates, which overstates strong winds (Cardone et al. 1990). There is the possibility that buoys may underestimate wind speeds in heavy seas, through wave sheltering effects. Because the SSMI is calibrated on buoy data, there is the possibility that SSMI may underestimate high wind speeds. Equally one must be aware that the ECMWF speeds could be affected by model biases and data biases (Andersson et al. 1991; Kelly et al. 1991). Further investigation is needed to narrow the uncertainties in each of the three different estimates we have used.

The time dependence of the annual mean SSMI and ECMWF wind speed differences is examined within the global 10°S - 10°N and 30 - 50°N regions. The 4-year longitudinal average mean difference of 0.75 m s^{-1} between 10°S and 10°N (Figure 3A) was significant. For each 2.5°-latitudinal band, the percent difference of the absolute value of the annual SSMI-ECMWF difference relative to the average of the annual mean SSMI and ECMWF wind speeds, which is named PD, was computed, i. e.,

$$PD = 100 \cdot (|SSMI - ECMWF|)/((SSMI + ECMWF)/2). \qquad (1)$$

For the global 10°S - 10°N region the annual mean PD values decreased approximately 4% each year from 1988 to 1991 (Figure 5). The change from 1988 to 1990 was significant, and each annual decrease from 1989 to 1991 was significant. In the 30 - 50°N region where the 4-year average longitudinal mean difference was large (Figure 3A), the annual SSMI and ECMWF percent difference did not become smaller, but showed a trend towards larger differences (Figure 5). The near doubling of the 30 - 50°N PD from 1989 to 1990 was significant.

The north-south profiles of the zonally averaged 4-year mean monthly standard deviations of the SSMI and ECMWF daily wind speed variations (Figure 3B) were similar to the profiles corresponding to each of the four annual intervals. The meridional profile of submonthly wind speed fluctuations had greater symmetry about the equator than that for wind speed (compare Figures 3A and 3B). From 60°S - 20°N the SSMI submonthly standard deviations were greater than the ECMWF values and from 30 - 60°N the ECMWF data were greater, which was similar to the north-south distribution of the SSMI and ECMWF wind speeds (compare Figures 3A and 3B). The SSMI standard deviations were larger in the 5 - 10°N region relative to that at 0° and 15°N (Figure 3B), which was expected because of the ITCZ from 5 - 10°N in the Atlantic and Pacific Oceans; however, the ECMWF analysis did not display this feature. Rain reduced the daily number of SSMI wind retrievals in the ITCZ to one (instead of two at other latitudes), which, presumably, would not lead to an increase in the monthly standard deviation of daily wind speeds.

Equation (1) was used to compute the percent difference between the SSMI and ECMWF monthly standard deviations of daily wind speed in each 2.5°-latitudinal band between 10°S - 10°N, where the 4-year mean difference of 0.5 m s^{-1} was significant. The 36% difference in 1988 was significantly higher than the 30% difference in 1989 but the year-to-year changes of the SSMI and ECMWF differences from 1989 to 1991 were not distinguishable from zero. In the 50 - 30°S region where the 4-year mean difference was large but not significant, the annual percent difference increased steadily from 6% in 1988 to 9% in 1991 when the difference was almost significant.

b. Arabian Sea

The 10 - 20°N, 60 - 70°E central Arabian Sea is an important tropical environment to study wind-driven ocean circulation and ocean-atmosphere interactions. Typical monthly mean SSMI wind speeds in May (before the onset of the southwest monsoon) and July (after the onset of the southwest monsoon) were 3 and 11 m s^{-1}, respectively. Because of extreme temporal variations of wind speed, the coupled ocean-atmosphere dynamics of the Arabian Sea is a prominent component of at least two major international programs (Smith et al. 1991; WMO 1992), which require accurate information about the surface wind field. For the central Arabian Sea, the ECMWF monthly mean wind speed was always equal to or greater than the SSMI value (Figure 6), in contrast to the global zonal average for the 10 - 20°N latitudes (Figure 3A). The COADS monthly mean wind speeds were usually 1 - 2 m s^{-1} greater than the SSMI data (Figure 6). Approximately 300 COADS data occurred in the central Arabian Sea each month during 1988 - 1991. The difference between COADS and ECMWF monthly mean wind speeds was less than that between COADS and SSMI data, which is not too surprising because the ECMWF analysis assimilates ship wind observations. Monthly mean COADS and ECMWF time series (Figure 6) were in better agreement than the COADS and SSMI data, especially during the summer monsoon. Each data set reproduces the periodicity associated with the southwest and northeast monsoons. The ECMWF wind speed during the southwest monsoon was typically 1 m s^{-1} or 8 - 10% higher than the SSMI measurement; however, the range of speeds between successive minimum and maximum values was nearly the same for the SSMI and ECMWF data. The largest annual-period SSMI and ECMWF wind speed difference was 1.0 m s^{-1} in 1991; yet, neither the 4-year nor the annual mean SSMI and ECMWF wind speeds were significantly different. The weakest agreement between SSMI and ECMWF monthly mean speeds occurred in July when the difference was 1.2 m s^{-1}, which was twice as large as in June. The standard deviations of the monthly mean ECMWF and SSMI wind speeds for each annual interval were almost the same at about 2.5 m s^{-1}.

c. *Equatorial Atlantic and Pacific*

The improving agreement between the tropical ECMWF and SSMI wind speeds between 1988 and 1991 (Figure 5) merits closer examination in the equatorial zone of the Pacific Ocean where the El Niño phenomenon occurs. Inspection of Figure 7 shows that during 1988 and 1989 the 5°S - 5°N SSMI and ECMWF monthly mean wind speed differences were typically 2.0 m s^{-1}, or about 35% of the SSMI wind speed, throughout 160°E - 160°W. In 1990 and 1991 the 160°E - 160°W wind speed differences dropped to 0.5 m s^{-1}, which corresponds to about 12 W m^{-2} surface heat flux uncertainty and which is the sensitivity required for studies of climate variations (Ramage 1984). The marked reduction in the SSMI and ECMWF differences in mid-1989 coincided with important changes to the ECMWF forecast-analysis system, which affected the convection scheme (Tiedtke 1989) and radiation transfer parameterization (Morcrette 1990). The model changes intensified the hydrological cycle and yielded stronger trade winds. The June 1990 change in the modeled latent heat flux formulation at low wind speed (Miller et al. 1992) did not seem to influence the ECMWF and SSMI wind speed differences in the equatorial Pacific (Figure 7).

Throughout the eastern Pacific from 140 - 100°W the SSMI and ECMWF differences were almost always smaller than 1.0 m s^{-1}, except near 110°W in May and June 1989 when differences reached 3.0 and 3.5 m s^{-1}, respectively. These large differences were anomalous because for each month the average monthly mean moored-buoy wind speed at 5°S, 2°S, 0°, 2°N, and 5°N along 110°W was within 0.9 m s^{-1} of the SSMI data, which was typical of the SSMI and moored-buoy matchups along the Pacific equator (Halpern 1993). The temporary problem was related to an incorrect GTS coding of the moored-buoy real-time wind measurements at and near the equator along 110°W.

The reduction with time of the SSMI and ECMWF difference in the 160°E - 160°W zone of the tropical Pacific (Figure 7) indicated an apparent improvement of the ECMWF tropical surface wind analysis (Figure 5). However, examination of the time series of monthly mean ECMWF wind speeds within 10°S - 10°N, 145°E - 85°W (Figure 8A) did not show the real decrease in wind speed that occurred over the equatorial Pacific because of the 1988 La Niña and 1991 El Niño episodes. Throughout the region, the annual mean SSMI wind speeds decreased gradually from 6.2 m s^{-1} in 1988 to 5.4 m s^{-1} in 1991, which was consistent with the change from La Niña to El

Niño conditions. Furthermore, the 0.4 m s^{-1} difference between the SSMI annual mean speeds in 1990 and 1991 was significant. In contrast, the annual mean ECMWF wind speeds were approximately constant with the largest difference between two consecutive annual means equal to 0.1 m s^{-1}, which was not significant. This suggests that as a consequence of the ECMWF model changes the time series of ECMWF surface wind speeds masks the real trend in equatorial Pacific wind speeds during 1988 - 1991. To confirm this result, we examined the annual mean wind speeds in the 10°S - 10°N, 45°W - 5°E area of the tropical Atlantic Ocean (Figure 8B) where the temporal variations of the ECMWF and SSMI wind speeds were opposite to those in the Pacific. In the Atlantic the successive annual mean SSMI wind speeds differed by less than 0.1 m s^{-1}, which was not significant, and the ECMWF speeds increased at an approximately uniform annual rate from 4.9 m s^{-1} in 1988 to 5.7 m s^{-1} in 1991, which was significant. The absence of interannual variability of the SSMI wind speed in the tropical Atlantic was consistent with the natural insensitivity of the surface wind field over the tropical Atlantic during El Niño and La Niña episodes (Halpert and Ropelewski 1989; Ropelewski and Halpert 1989).

4. Conclusions

In an examination of the impact of the changes made to the ECMWF forecast-analysis system upon the monthly mean ECMWF surface wind speed during 1988 - 1991, the SSMI global wind speed measurements were considered to be a reference data set. In the 30 - 50°N region of the Atlantic and Pacific Oceans the longitudinal average ECMWF monthly mean wind speed was greater than that computed from SSMI data (Figure 3A). At other latitudes the zonal mean SSMI wind speed was larger than the ECMWF speed (Figure 3A). The SSMI and ECMWF wind speed difference was twice as large in the northern hemisphere extratropics (0.8 m s^{-1}) than in the southern hemisphere extratropics (0.4 m s^{-1}). The SSMI and ECMWF speed differences in the northern hemisphere extratropics probably derive from the use of ship wind measurements in the ECMWF assimilation. In these latitudes, large quantities of ship wind speed are available. The ECMWF and ship wind speeds were close to each other in the North Atlantic Ocean (Figure 4), and both differed from the SSMI speeds by similar amounts. Analogous results were found in the Arabian Sea (Figure 6), which is one of the few tropical areas where ship data are available in quantity. These results raise two issues: the quality of ship winds used at NWP centers, and the quality of buoy winds used to calibrate satellite data. There are many problems in the wind reports (Pierson 1990; Cardone et al. 1990). Also, there are concerns that buoy anemometers may be affected by wave sheltering. No single data source is likely to be free of error. Comparison of operational surface wind analysis computed with and without assimilation of surface wind observations from ships would be informative.

The dominant data source for the ECMWF analyses in the southern hemisphere were the operational NOAA National Environmental Satellite Data and Information Service retrievals from TIROS Operational Vertical Sounder radiance data. Repeated experimentation at ECMWF shows that it is very difficult to run a stable assimilation in the southern hemisphere without this data. The tendency of the retrievals to underestimate the intensity of baroclinic temperature gradients has been extensively documented by Andersson et al. (1991) and Kelly et al. (1991).

In the tropical zone the difference between ECMWF and SSMI monthly mean wind speeds (Figure 3A) was significant, and the differences became significantly smaller with time (Figure 5). As a result of the changes of the ECMWF model rather than improvements in data availability, the time series of monthly mean ECMWF analyzes did not reflect the true trend in the wind speeds, but rather masked the trend. The decrease of the differences in the tropical Pacific (Figure 7) were generated by natural variations associated with La Niña and El Niño, which the SSMI data reproduced but which were not represented by ECMWF (Figure 8A). Similarly, the decrease of the SSMI and ECMWF wind speed differences in the tropical Atlantic were also ascribed to natural variability which were not monitored by ECMWF (Figure 8B). Caution is therefore advised in using ECMWF wind speeds to interpret interannual fluctuations of air-sea fluxes, such as the the amount of carbon dioxide degassing from the equatorial Pacific during La Niña and El Niño episodes.

Tropical ECMWF wind speeds were significantly smaller than SSMI measurements (Figure

3A). This illustrates the difficulty in modeling surface winds in the tropics because the ECMWF forecast-analysis system assimilated numerous low-level cloud motions, which had monthly mean speeds nearly 2.5 m s^{-1} or 50% greater than the 10-m wind speed at the equator (Halpern and Knox 1983) and which had special error characteristics (Le Marshall et al. 1992). Since the time of the initial ECMWF analyses in 1980, the ECMWF surface wind analysis in the tropics had speeds too low (Trenberth et al. 1990) and contained an unrealistic ITCZ south of the equator in the eastern Pacific (Trenberth 1992). The TOGA Tropical Atmosphere-Ocean (TAO) array of moored-buoy real-time wind measurements (Hayes et al. 1991), which would be transmitted on the GTS for retrieval by NWP centers, were intended to overcome the lack of high-quality surface wind observations in the data-sparse tropical Pacific. Implementation of the 70-element TAO array began in 1988 and was nearly 50% completed by December 1991. However, very little TAO data were transmitted on the GTS during January 1988 - December 1991, e. g., the flow of TAO data on the GTS increased from 30% in September 1992 to 90% in December 1992. Additional evaluations of the ECMWF tropical wind analysis are warranted after deployment of the TAO array, which is scheduled for 1994.

Acknowledgements. We are grateful to Drs. A. Guillaume, P. Janssen and B. Hansen, all of ECMWF, and Dr. E. Sarachik, University of Washington, for helpful comments and suggestions. We thank Steven Worley, NCAR, who kindly sent COADS data immediately upon request. William Knauss, JPL, developed the computer software to track, display and analyze millions of numbers, all in his usual outstanding fashion. This work was supported by NASA UPN 578-22-26-40 (DH) and by the NSCAT Project (DH), which are gratefully acknowledged. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Andersson, E., A. Hollingsworth, G. Kelly, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991:

Global observing system experiments on operational statistical retrievals of satellite sounding data. *Monthly Weather Review*, **119**, 1851-1864.

Cardone, V. J., J. G. Greenwood, and M. A Cane, 1990: On trends in historical marine wind marine wind data. *Journal of Climate*, **3**, 113-127.

Esbensen, S. K., and Y. Kushnir, 1981: The heat budget of the global oceans: An atlas based on estimates from surface marine observations. Report No. 29, Climate Research Institute, Oregon State University, Corvallis, 27 pp + figures.

Esbensen, S. K., D. B. Chelton, D. Vickers, and J. Sun, 1993: An analysis of errors in SSM/I evaporation estimates over the global ocean. *Journal of Geophysical Research*, in press.

Halpern, D., 1993: Validation of Special Sensor Microwave Imager monthly mean wind speed from July 1987 to December 1989. *IEEE Transactions on Geoscience and Remote Sensing*, **31**, 692-699.

Halpern, D., 1991: The NASA Ocean Data System at the Jet Propulsion Laboratory. *Advances in Space Research*, **11**, 255-262.

Halpern, D., 1989: Seasat-A satellite scatterometer measurements of equatorial surface winds. *Journal of Geophysical Research*, **94**, 4829-4833.

Halpern, D., 1988a: On the accuracy of monthly mean wind speeds over the equatorial Pacific. *Journal of Atmospheric and Oceanic Technology*, **4**, 362-367.

Halpern, D., 1988b: Moored surface wind observations at four sites along the Pacific equator between 140° and 95°W. *Journal of Climate*, **1**, 1251-1260.

Halpern, D., 1987: Comparison of moored wind measurements from a spar and toroidal buoy in the eastern equatorial Pacific during February - March 1981. *Journal of Geophysical Research*, **92**, 8303-8306.

Halpern, D., and R. A. Knox, 1983: Coherence between low-level cloud motion vectors and surface easterly tradewind measurements near 0°, 152°W from April 1979 to February 1980. *Atmosphere-Ocean*, **21**, 82-93.

Halpern, D., W. Knauss, O. Brown, and F. Wentz, 1993: An atlas of monthly mean distributions of SSMI surface wind speed, ARGOS buoy drift, AVHRR/2 sea surface temperature, and ECMWF surface wind components during 1990. JPL Publication 93-1, Jet Propulsion Laboratory, Pasadena, 111 pp.

Halpern, D., E. Harrison, B. Hinton, R. Long, M. Mathur, J. O'Brien, S. Payne, S. Pazan, and J. Sadler, 1982: Intercomparison of tropical Pacific mean November 1979 surface wind fields. Technical Report, Department of Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, 40 pp.

Halpert, M. S., and C. F. Ropelewski, 1989: Atlas of tropical sea surface temperature and surface winds. NOAA Atlas No. 8, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, 13 pp text, 158 diagrams. (Available from Climate Analysis Center, W/NMC52, 5200 Auth Road, Washington, DC 20233)

Hayes, S.P., L.J. Mangum, J. Picaut, and K. Takeuchi, 1991: TOGA-TAO: A moored array for real-time measurements in the tropical Pacific Ocean. *Bulletin of the American Meteorological Society*, **72**, 339-347.

Hoskins, B. J., H. H. Hsu, I. N. James, M. Masutani, P. D. Sardeshmukh, and G. H. White, 1989: Diagnostics of the global atmospheric circulation based on ECMWF analyses 1979 - 1989. WMO/TD-No. 326, World Meteorological Organization, Geneva, 217 pp.

Hsiung, J., 1986: Mean surface energy fluxes over the global ocean. *Journal of Geophysical Research*, **91**, 10585-10606.

Kelly, G., E. Andersson, A. Hollingsworth, P. Lönnberg, J. Pailleux, and Z. Zhang, 1991: Quality control of operational physical retrievals of satellite sounding data. *Monthly Weather Review*, **119**, 1866-1880.

Legler, D. M., 1991: Errors of five-day mean surface wind and temperature conditions due to inadequate sampling. *Journal of Atmospheric and Oceanic Technology*, **8**, 705-712.

Le Marshall, J., N. Pescod, G. Mills, and P. Stewart, 1992: Cloud drift winds in the Australian Bureau of Meteorology: An operational note. *Australian Meteorological Magazine*, **40**, 247-250.

Miller, M. J., A. C. M. Beljaars, and T. N. Palmer, 1992: The sensitivity of the ECMWF model to the parameterization of evaporation from the tropical ocean. *Journal of Climate*, **5**, 418-434.

Morcrette, J. J., 1990: Impact of changes to the radiation transfer parameterizations plus cloud optical properties in the ECMWF model. *Monthly Weather Review*, **118**, 847-873.

Pierson, W. J., 1990: Examples of, reasons for, and consequences of the poor quality of wind data from ships for the marine boundary layer: Implications for remote sensing. *Journal of Geophysical Research*, **95**, 13313-13340.

Ramage, C. S., 1984: Can shipboard measurements reveal secular changes in tropical air-sea flux? *Journal of Climate and Applied Meteorology*, **23**, 187-193.

Ropelewski, C. F., and M. S. Halpert, 1989: Precipitation patterns associated with the high index phase of the Southern Oscillation. *Journal of Climate*, **2**, 268-284.

Smith, S. L., K. Banse, J. K. Cochran, L. A. Codispoti, H. W. Ducklow, M. E. Luther, D. B. Olson, W. T. Peterson, W. L. Prell, N. Surgi, J. C. Swallow, and K. Wishner, 1991: U.S. JGOFS: Arabian Sea Process Study. U.S. JGOFS Planning Report No. 13, Woods Hole Oceanographic Institution, Woods Hole, 164 pp.

Tiedtke, M., 1989: A comprehensive mass flux scheme for cumulus parameterization in large scale models. *Monthly Weather Review*, **117**, 1779-1800.

Trenberth, K. E., 1992: Global analyses from ECMWF and atlas of 1000 to 10 mb circulation statistics. Technical Note NCAR/TN-373+STR, National Center for Atmospheric Research, Boulder, 191 pp.

Trenberth, K. E., W. G. Large, and J. G. Olson, 1990: The mean annual cycle of the global ocean wind stress. *Journal of Physical Oceanography*, **20**, 1742-1760.

Wentz, F., 1992: Measurement of oceanic wind vector using satellite microwave radiometers. *IEEE Transactions on Geoscience and Remote Sensing*, **30**, 960-972.

Wentz, F., 1989: User's manual SSMI geophysical tapes. Technical Report 060989, Remote sensing Systems, Santa Rosa, California, 16 pp.

WMO, 1992: Simulation of interannual and intraseasonal monsoon variability. WCRP-68, WMO/TD-No. 470, World Meteorological Organization, Geneva, 224 pp.

Figure 1. Scatter diagram and orthogonal regression line between SSMI and moored-buoy matchups of (A) monthly mean wind speed and (B) monthly standard deviation of daily wind speed.

Figure 2. The 1988 - 1991, 2.5°- x 2.5°-resolution, 10-m height mean wind speeds (m s^{-1}) computed from (A) SSMI measurements and (C) ECMWF analyses, and the 4-year mean monthly standard deviations of (B) SSMI and (D) ECMWF daily wind speeds.

Figure 3. North-south profiles of the SSMI (solid line) and ECMWF (dashed line) longitudinally averaged, 1988 - 1991, 2.5°-latitudinal resolution, 10-m height mean wind speeds.

Figure 4. Monthly mean COADS (dashed line), ECMWF (dotted line), and SSMI (solid line) 10-m wind speed variations during 1988 - 1991 over the 30 - 25°N, 40 - 20°W North Atlantic Ocean.

Figure 5. Annual percent differences (see text for definition) between SSMI and ECMWF longitudinally averaged, 1988 - 1991, 2.5°-latitudinal resolution, 10-m height mean wind speeds for the 10°S - 10°N (solid line) and 30 - 50°N (dotted line) regions.

Figure 6. Monthly mean COADS (dashed line), ECMWF (dotted line), and SSMI (solid line) 10-m height wind speed variations during 1988 - 1991 over the 10 - 20°N, 60 - 70°E central Arabian Sea.

Figure 7. Time variations of the 5°S - 5°N, 2.5°-longitude monthly mean 10-m height SSMI-minus-ECMWF wind speed differences along the Pacific equator from 145°E to 85°W during 1988 - 1991. Contour interval is 0.5 m s^{-1}. Positive contours are solid lines and negative contours are dashed lines. Differences between 1 - 2 and 2 - 3 m s^{-1} are light and dark shaded, respectively. Differences greater than 3 m s^{-1} are shown in black.

Figure 8. Monthly mean area-weighted annual mean wind speeds for (A) the 10°S - 10°N, 145°E - 85°W area of the tropical Pacific Ocean and (B) the 10°S - 10°N, 45°W - 5°E region of the tropical Atlantic Ocean.

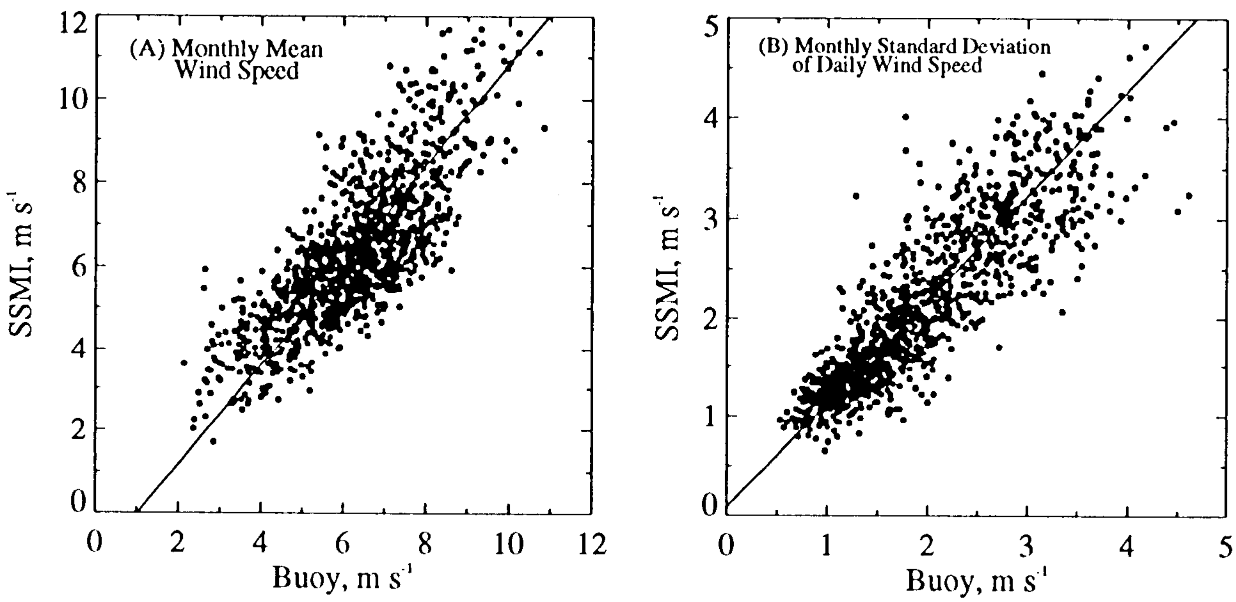
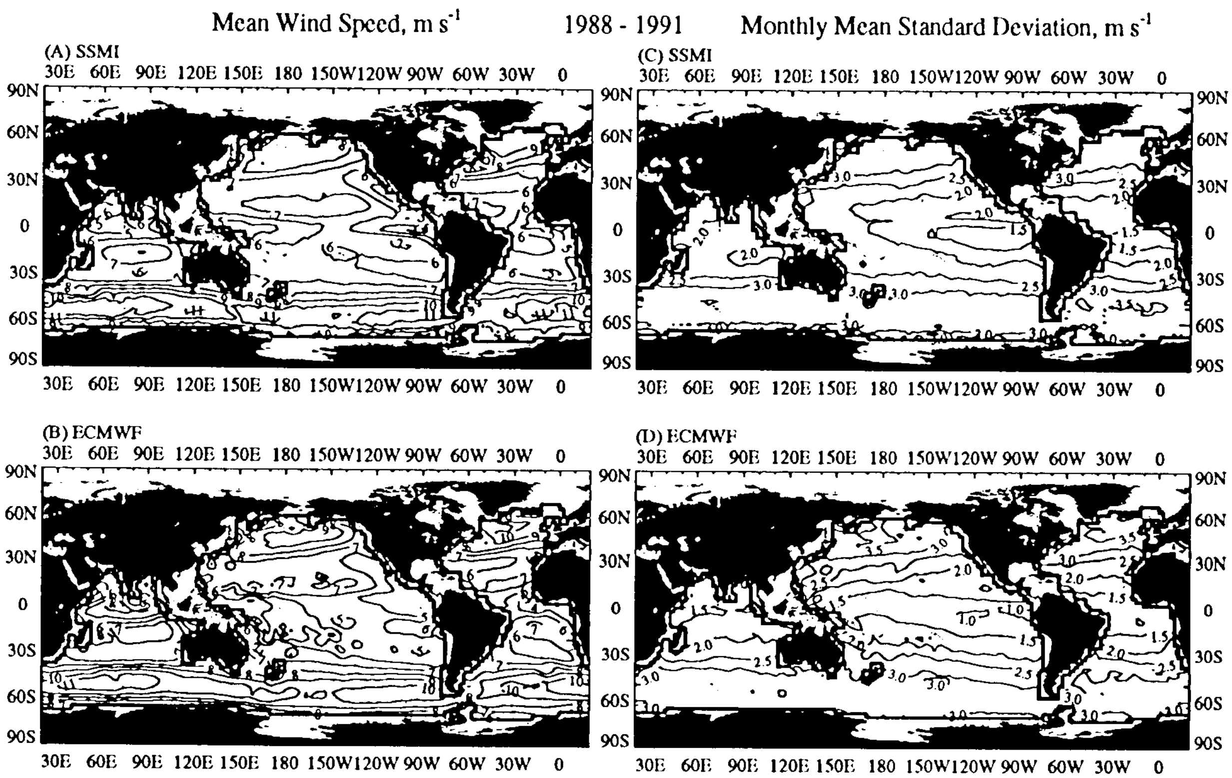
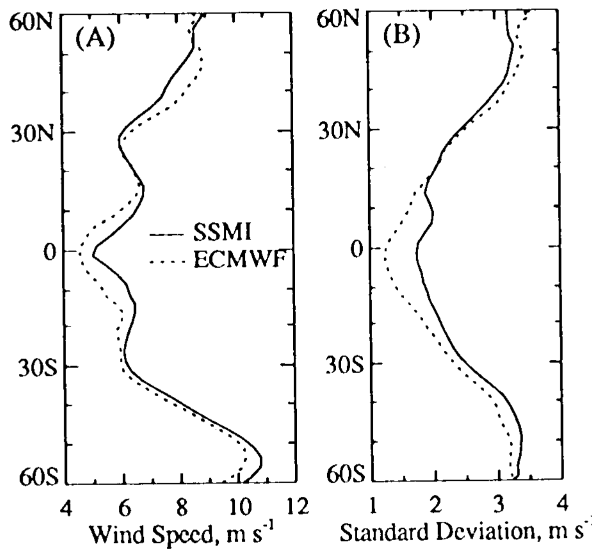

(A) Monthly Mean
Wind Speed
SSMI, m s-1
Buoy, m s-1
0
2
4
6
8
10
12
(B) Monthly Standard Deviation
of Daily Wind Speed
0
1
2
3
4
5

Figure 1



Mean Wind Speed, m s^{-1}
1988 - 1991
Monthly Mean Standard Deviation, m s^{-1}
(A) SSMI
(B) ECMWF
(C) SSMI
(D) ECMWF
30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0
90N 60N 30N 0 30S 60S 90S

Figure 2



(A)
(B)
60N
30N
0
30S
60S
SSMI
ECMWF
4
6
8
10
12
1
2
3
4
Wind Speed, m s-1
Standard Deviation, m s-1

Figure 3

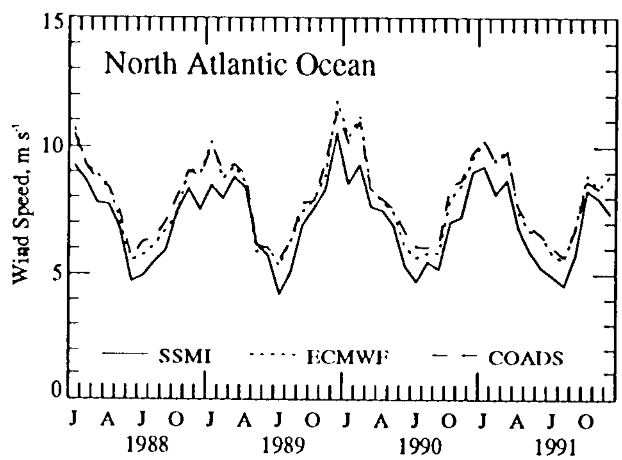
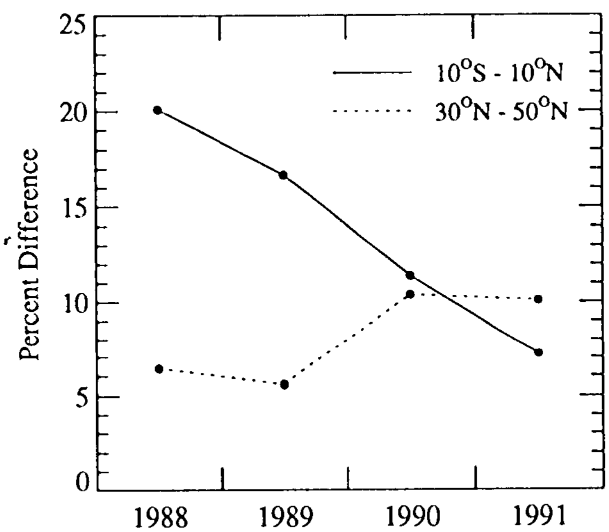
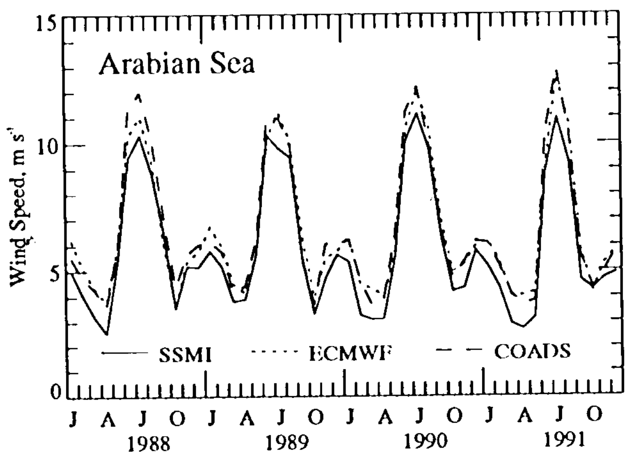

North Atlantic Ocean
Wind Speed, m s⁻¹
15
10
5
0
SSMI
ECMWF
COADS
J A J O J A J O J A J O J A J O
1988
1989
1990
1991

Figure 4



25
20
15
10
5
0
Percent Difference
10°S - 10°N
30°N - 50°N
1988
1989
1990
1991

Figure 5



Arabian Sea
Wind Speed, m s⁻¹
15
10
5
0
SSMI
ECMWF
COADS
J A J O J A J O J A J O J A J O
1988
1989
1990
1991

Figure 6

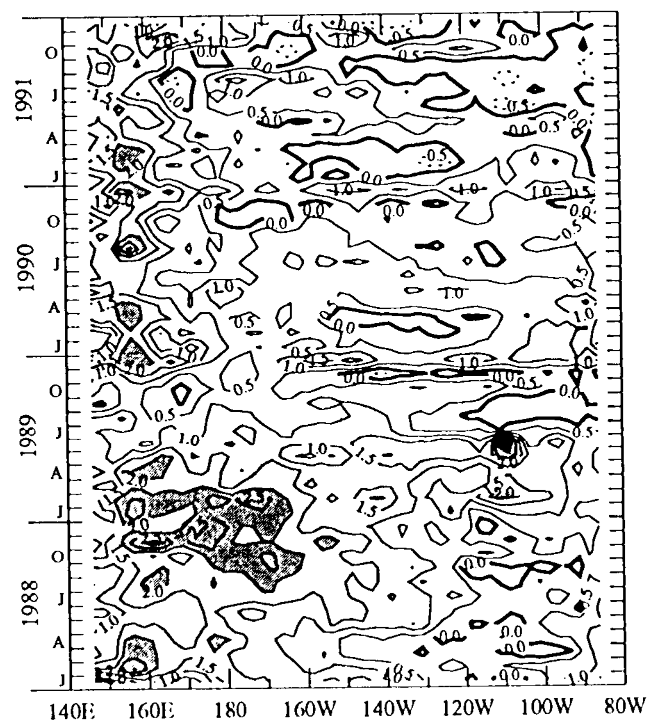


Figure 7

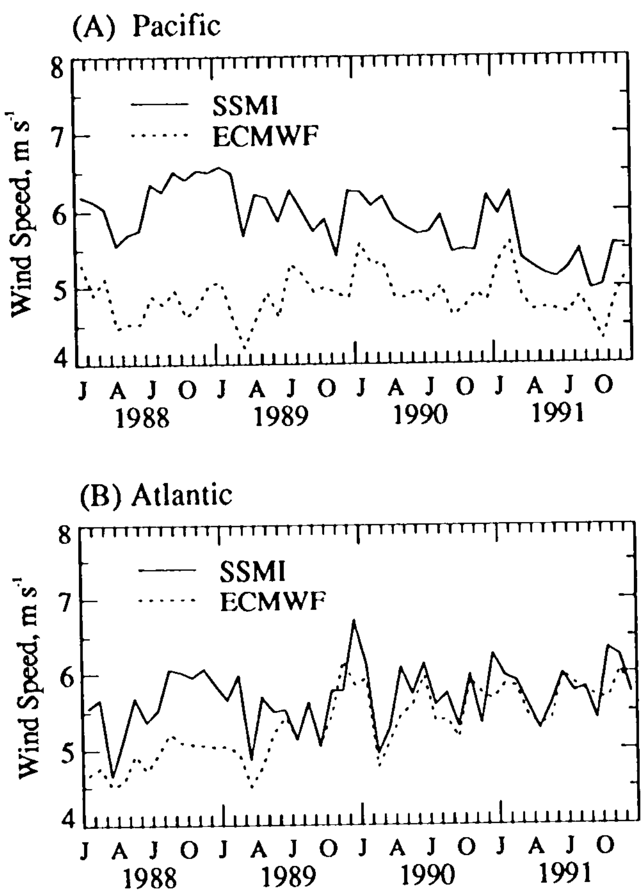

(A) Pacific
8
7
6
5
4
SSMI
ECMWF
Wind Speed, m s-1
J A J O J A J O J A J O J A J O
1988
1989
1990
1991
(B) Atlantic
8
7
6
5
4
SSMI
ECMWF
Wind Speed, m s-1
J A J O J A J O J A J O J A J O
1988
1989
1990
1991

Figure 8